

The background of the slide features a close-up of a human hand touching a blue liquid surface, creating concentric ripples. Numerous small, multi-colored squares (red, yellow, green, blue, purple) are scattered across the water's surface, some appearing to be floating or caught in the ripples. The overall image has a clean, professional aesthetic with a focus on environmental and technological themes.

International Conference on Greenhouse Gas Technologies



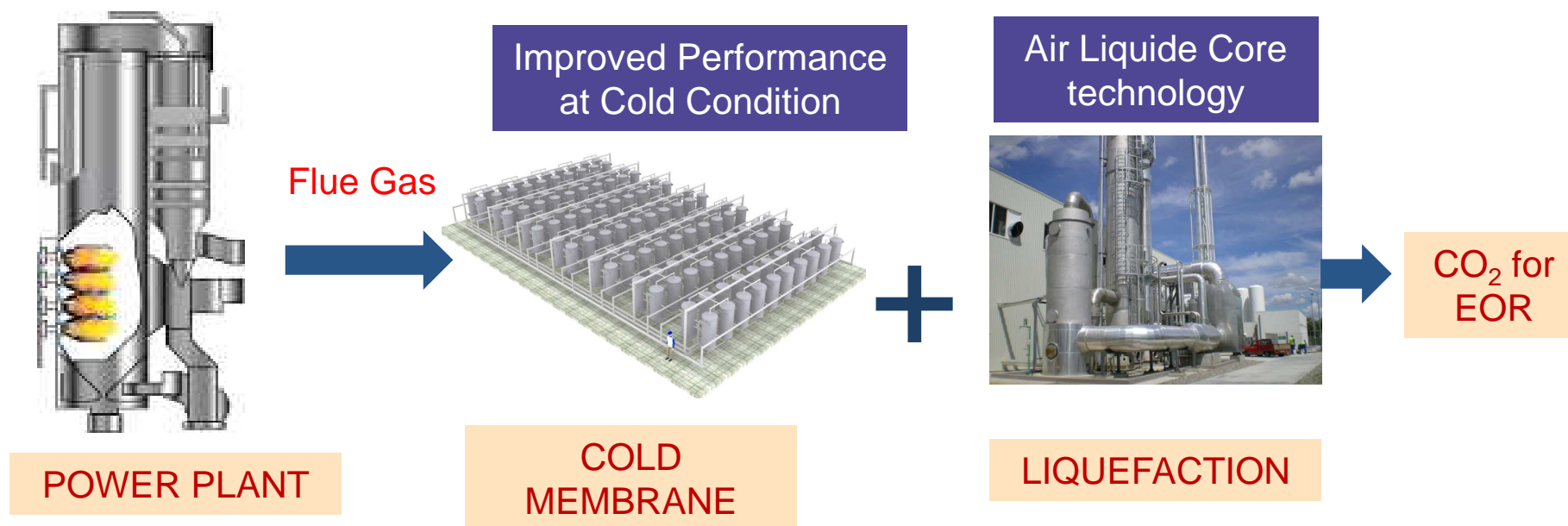
CO₂ Capture by Cold Membrane Operation

October 8th, 2014

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Project Summary

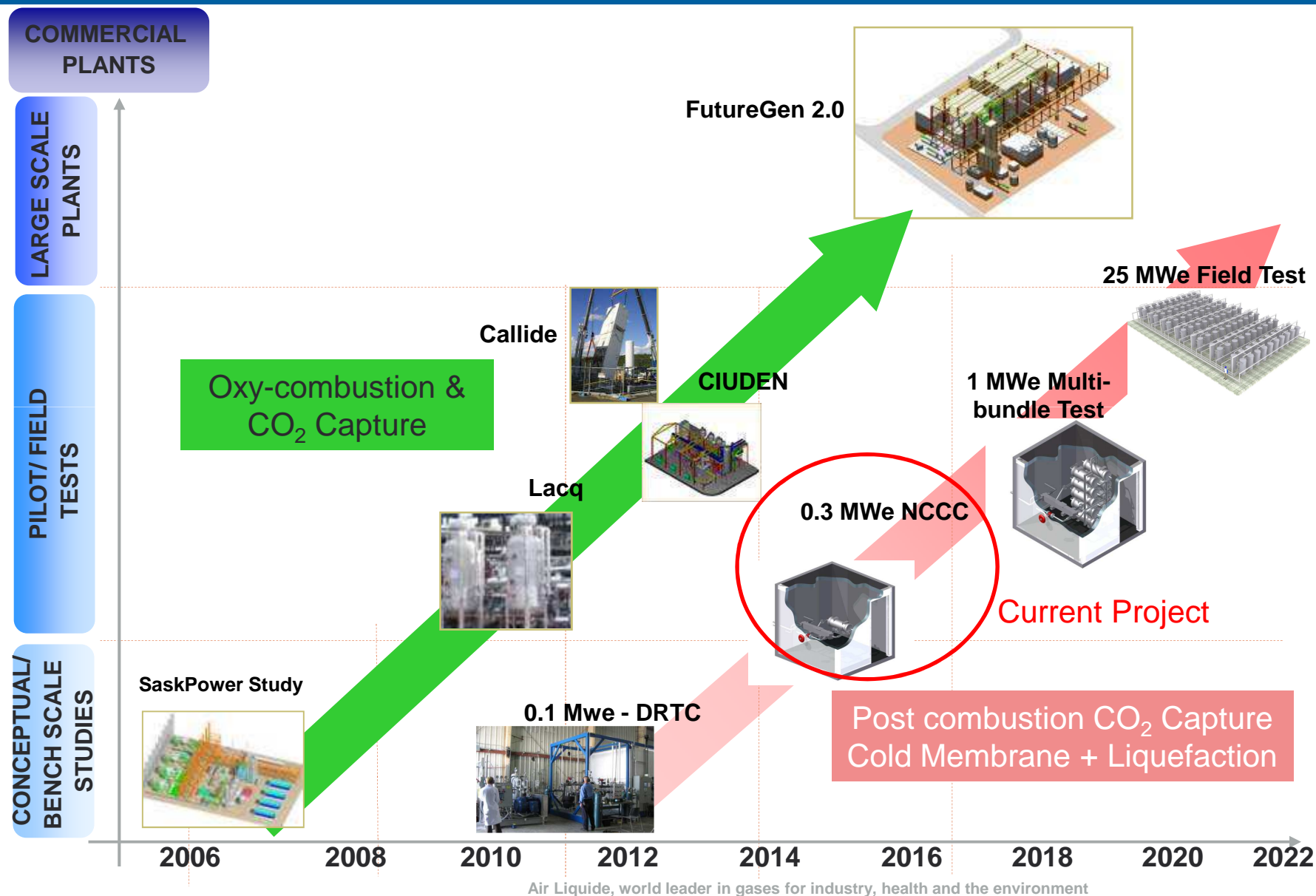
- Air Liquide Hybrid Cold Membrane - Liquefaction Process plant for 550 MWe scale



- Cold membrane testing was completed with synthetic flue gas (TRL4) in 2012
- Current project will test the cold membrane technology with real flue gas at 0.3 MWe (TRL5) using field test unit at National Carbon Capture Center (NCCC)



Air Liquide Roadmap for Power Plant CO₂ Capture Technologies



Acknowledgment

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Agenda

- Membrane Overview
- Capture Technology
- Testing with Synthetic Flue Gas
- Testing with Actual Flue Gas
- Future



Air Liquide: Key Information



A world leader in industrial and medical gases

> 50,000 employees

\$19.5 billion sales (2013)



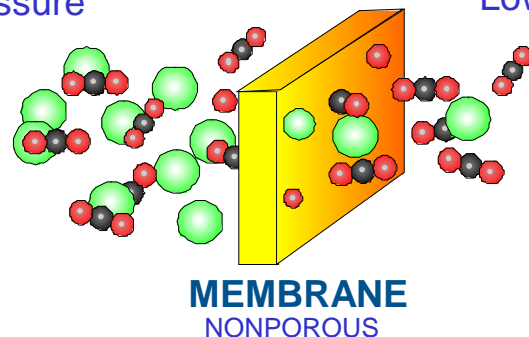
Proposed new technology leverages AL strengths

- Air Liquide MEDAL™ – Established membrane manufacturer for N₂, H₂ and CO₂ applications
- Air Liquide core expertise in gas separation, cryogenics and gas handling
- Strong program related to coal oxy-combustion

Membrane Science

FEED
High pressure

PERMEATE
Low pressure



Performance Measures

PERMEABILITY

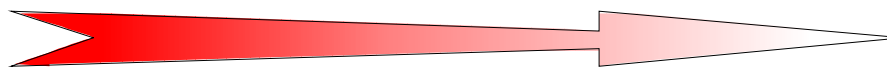
$$P = D(c) * S(c)$$

SELECTIVITY

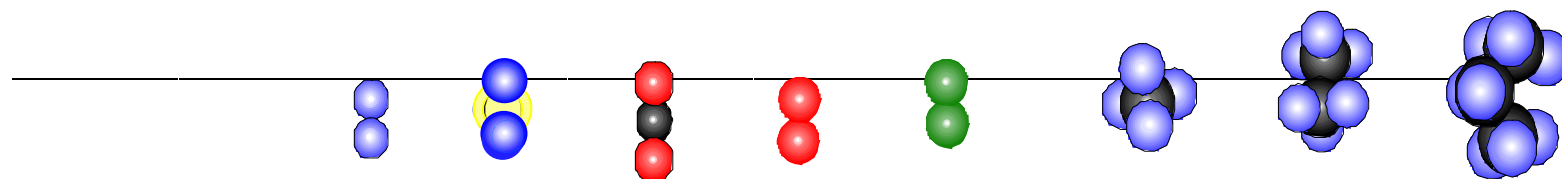
$$\alpha = \left[\frac{P_1}{P_2} \right] = \left[\frac{D_1}{D_2} \right] \left[\frac{S_1}{S_2} \right]$$

Permeability is determined by the product of solubility and diffusivity

FAST



SLOW



H_2

H_2S

CO_2

O_2

N_2

CH_4

C_2H_6

C_3H_8

Solubility- T_c (K)

33

373

304

155

126

191

307

370

Diffusion-Diameter (Å)

2.9

3.7

3.3

3.4

3.6

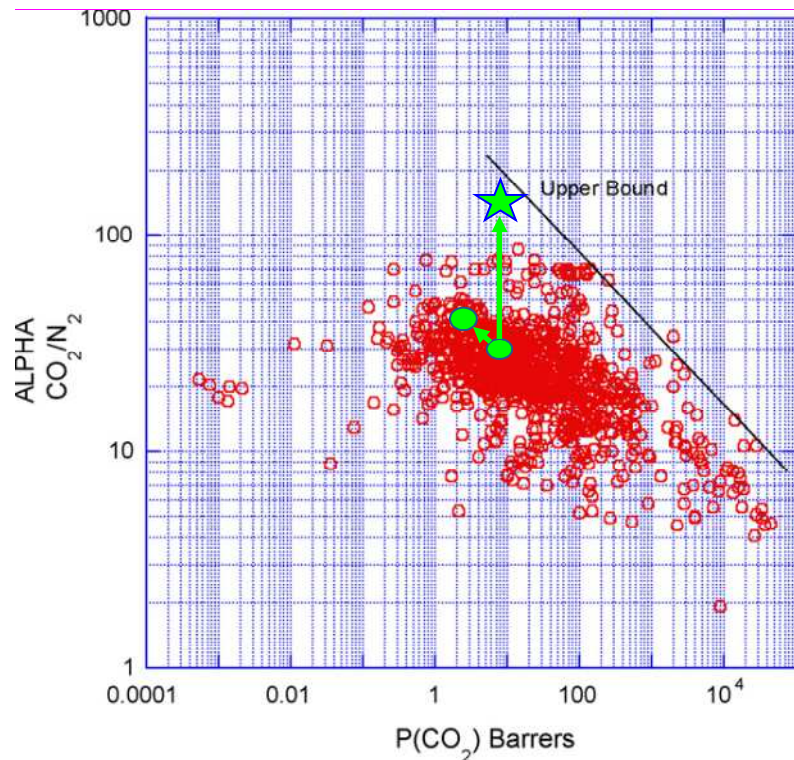
3.8

3.8

4.2

Cold Membrane Performance

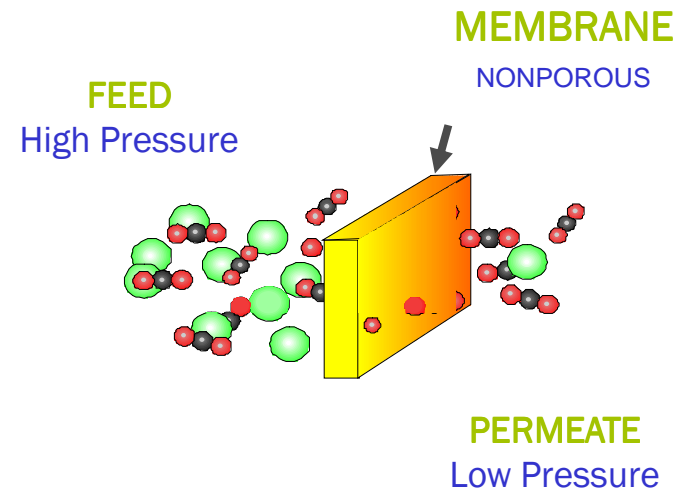
Existing AL Membrane operated at $< -10^{\circ}\text{C}$
has unique combination of high CO_2
permeance and CO_2 / N_2 selectivity



Robeson, JMS, 2008

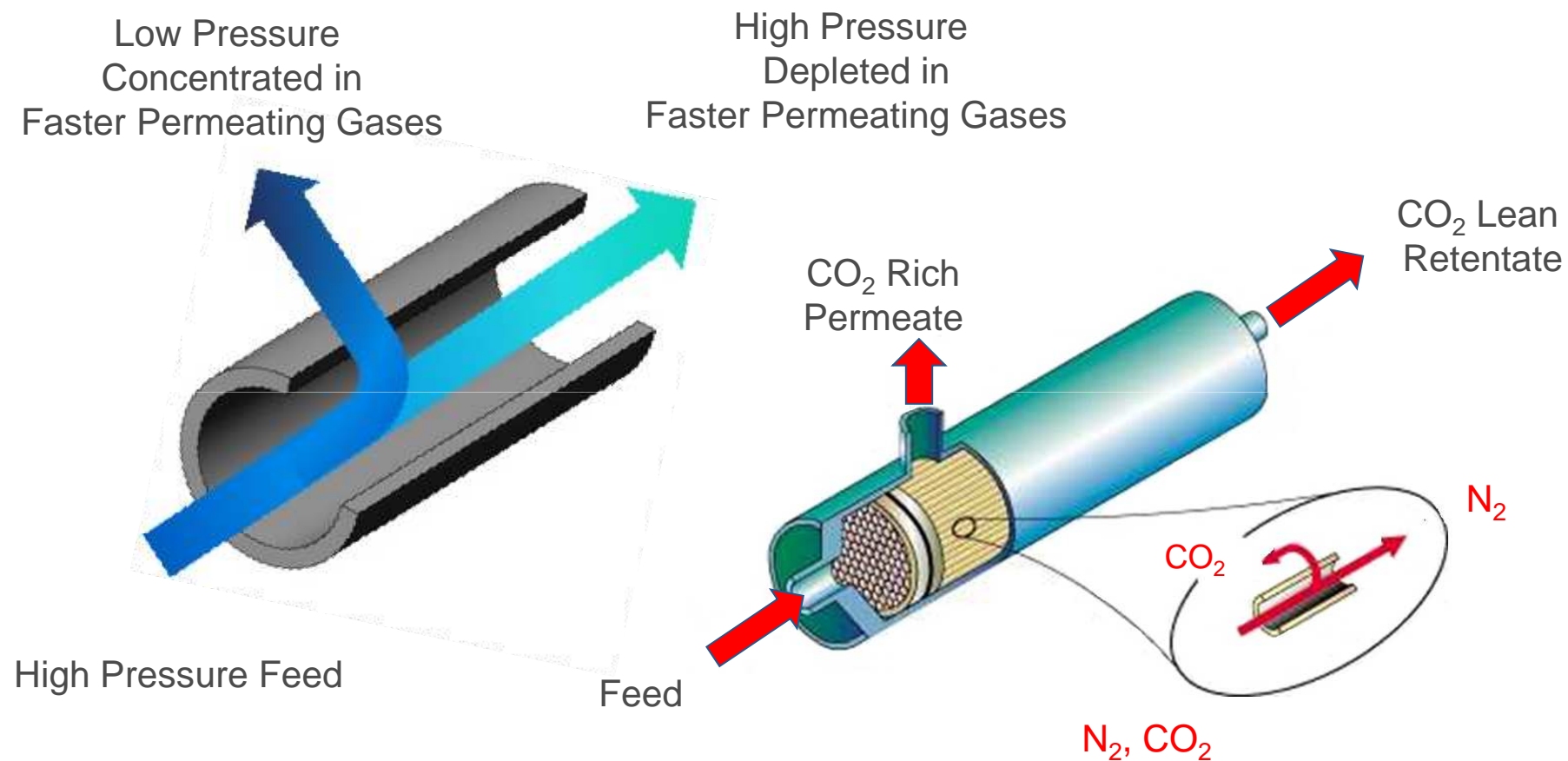


Intrinsic permeability at -30°C inferred from known
film data at RT + fiber data at RT and -30°C



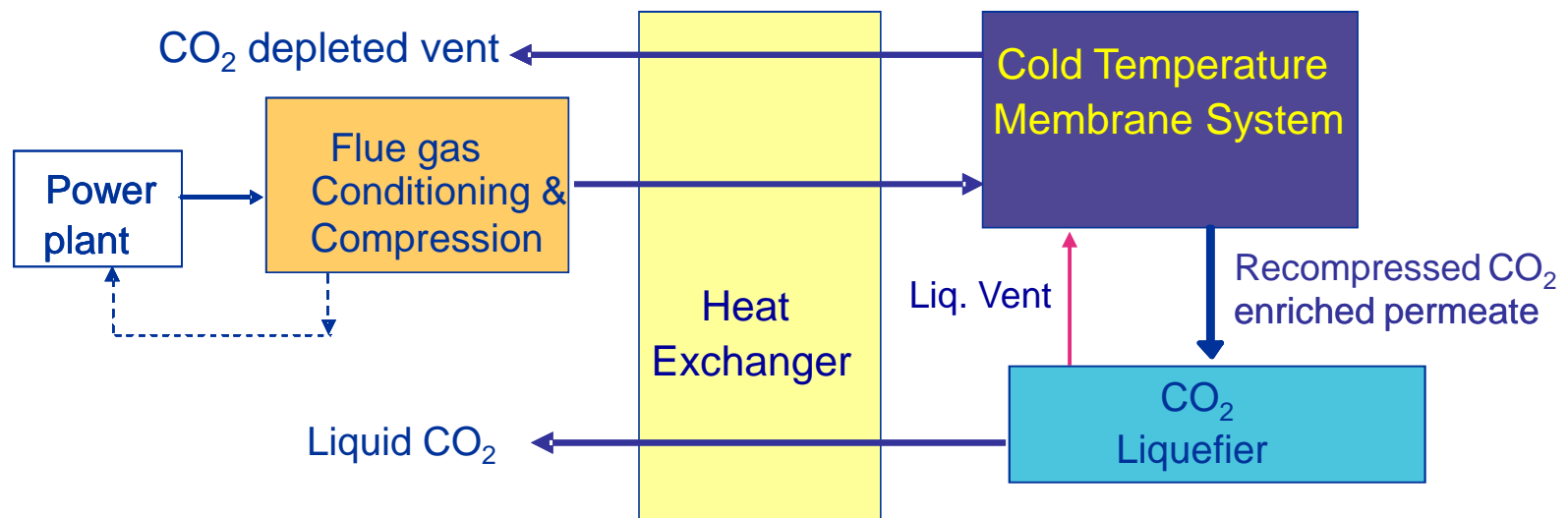
$$\Delta E_P = \Delta E_D + \Delta H_S$$

Hollow Fiber Membranes

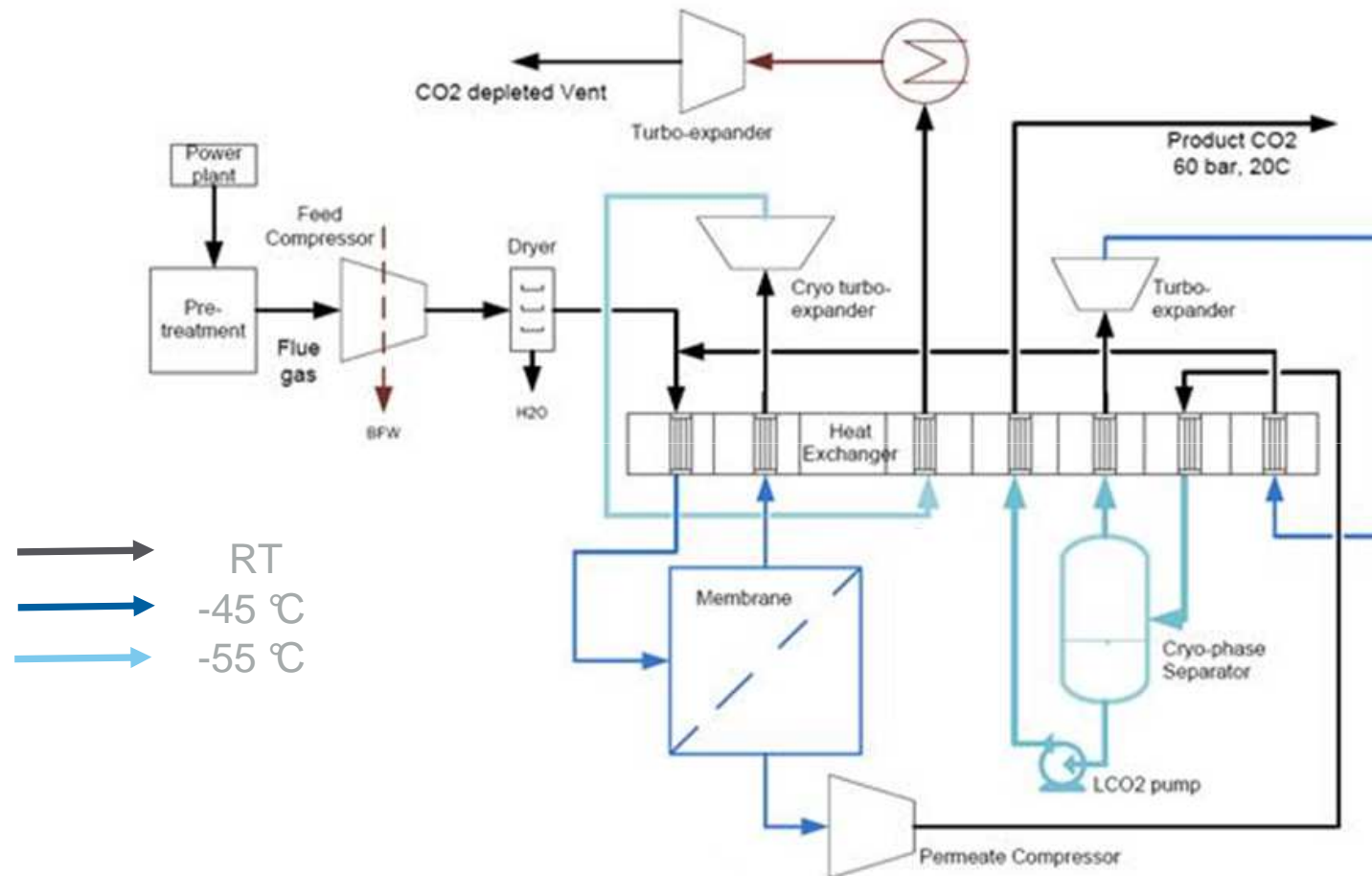


Cold Membrane Process Design Concept

- Pre-concentration of CO₂ by **highly selective cold membrane** before liquefier
- **Energy integration** between membrane / liquefier through heat exchange
- **Efficient recovery** of compression energy



Hybrid Membrane + Liquefaction Configuration



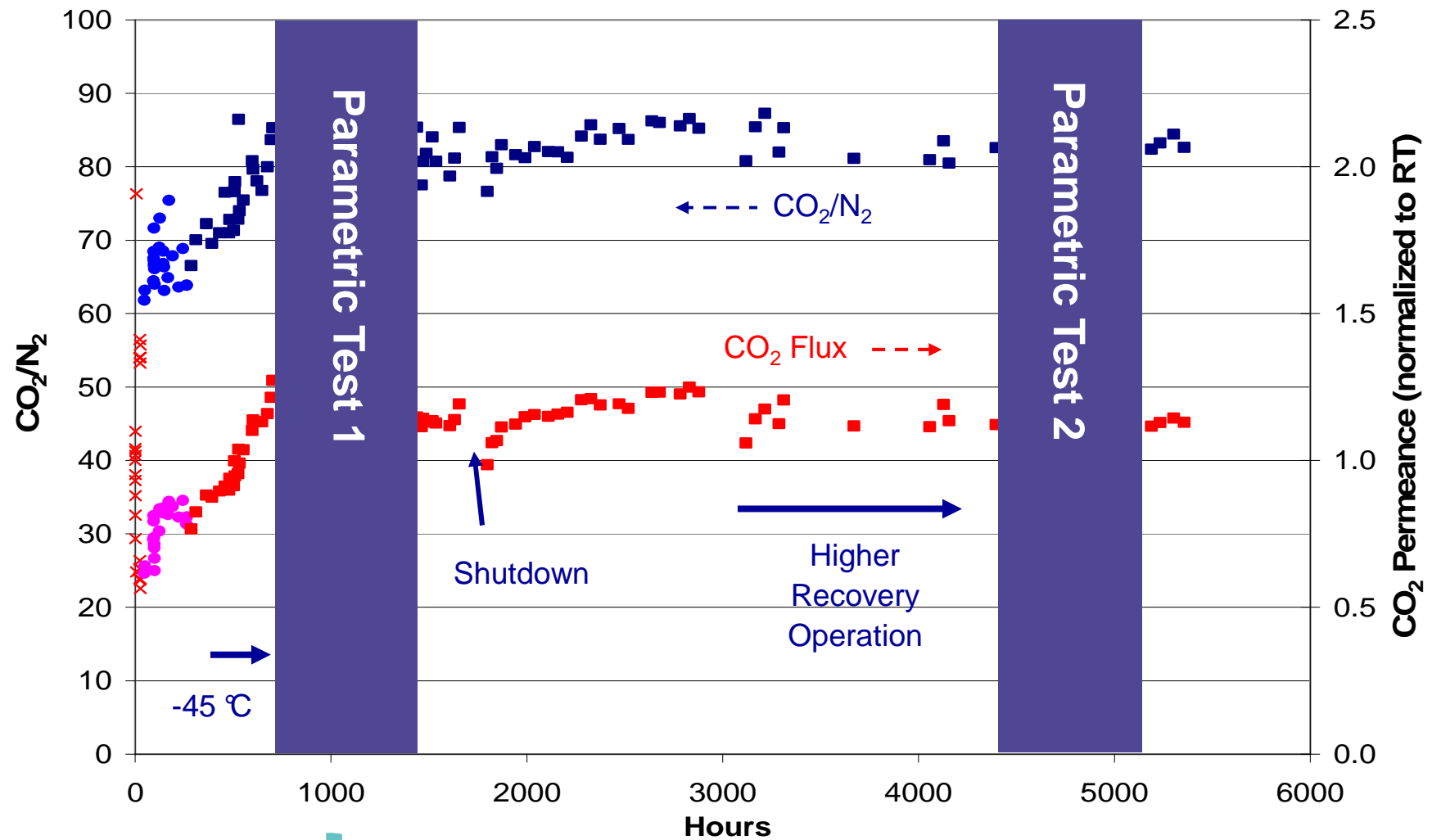
This second generation carbon capture technology integrates new cold membrane technology into the known liquifier solution

Initial Synthetic Flue Gas Testing

0.1 MWe Bench Scale Skid



Endurance Testing with 6" Bundle: 6 Month Test



Techno-economic Evaluation

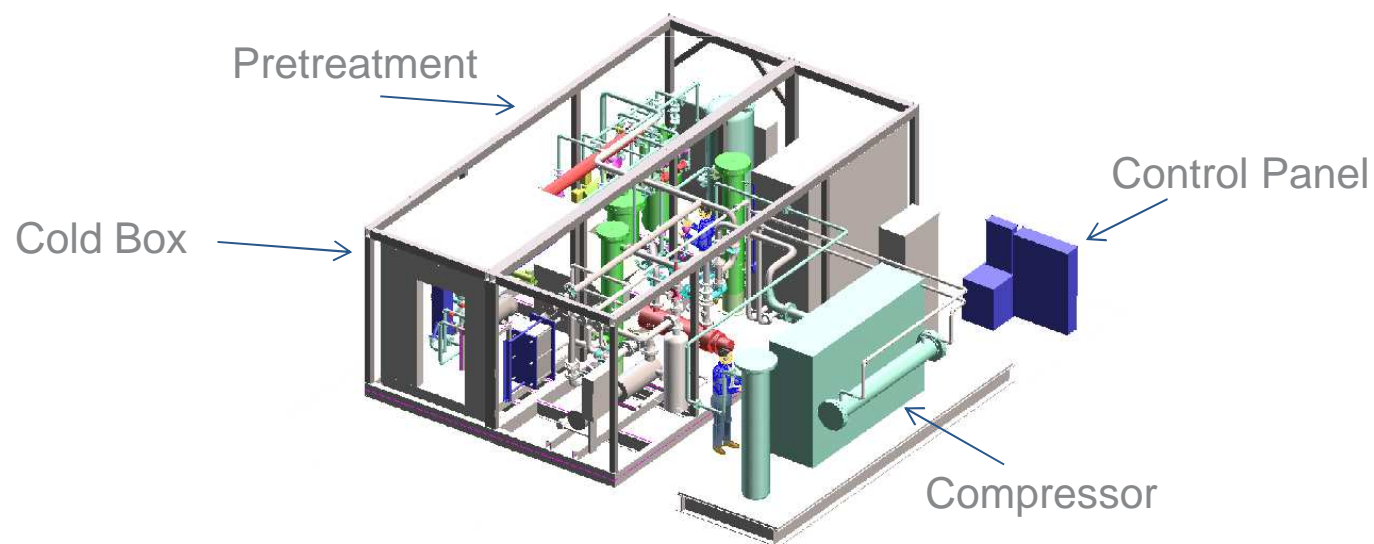
- At the end of our first project DE-FE0004278, the economics of this approach were evaluated to calculate the levelized cost of electricity (LCOE) for 90% CO₂ capture from a 550 MW net air-fired coal power plant. The costing methodology followed DOE/NETL study 2010/1397 [14].
- Equipment costs were based on quotations available `today and thus represent a 1st of a kind plant.

	DOE/NETL Case 11 (Amines)	Cold Membrane Hybrid
% Increase in LCOE	74.4%	48-53%



Current Project

- Improve scale up of 6" bundles to 12" bundles
 - Scaling is more difficult with high performing cold temperature modules
- Design and fabricate a membrane skid for testing 12" modules at the National Carbon Capture Center (Wilsonville AL) This test is scheduled for 2015.



Ideal Membrane Bundle

Maximizes partial pressure difference

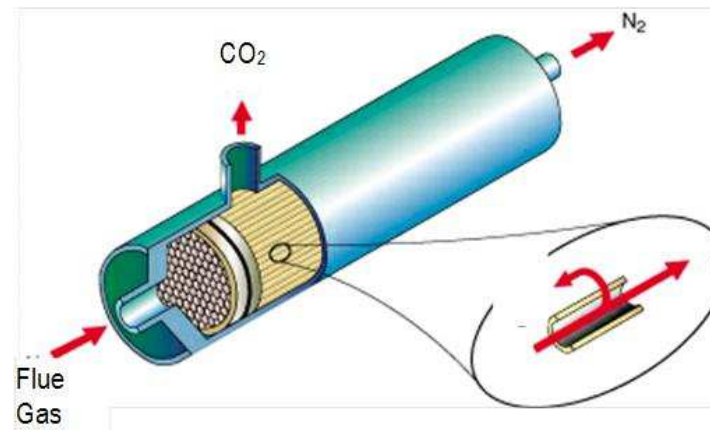
- Perfect Counter Current Flow

- Uniform fiber performance

- Uniform fiber dimension

- Uniform packing density

- Defect / Leak free



CFD Model Results

■ Ideal Membrane Bundle

CFD RESULTS

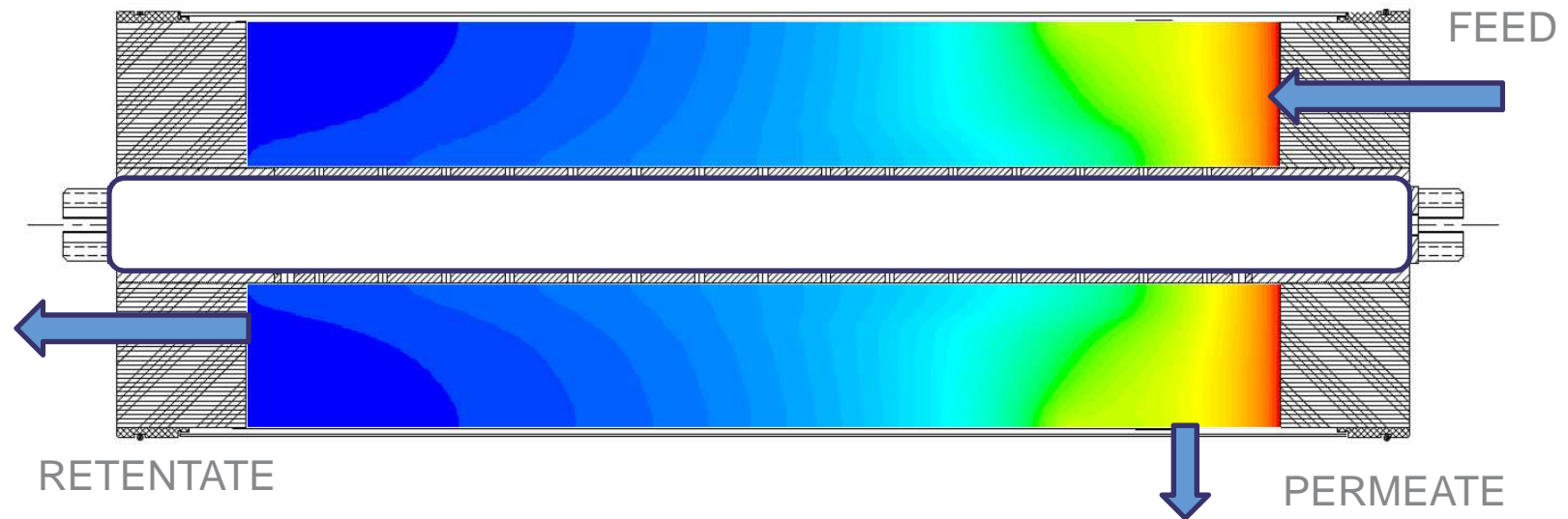
■ Perfect Counter Current Flow	→	Critical
■ Uniform fiber performance	→	Not Critical
■ Uniform fiber dimension	→	Not Evaluated
■ Uniform packing density	→	Important
■ Defect / Leak free	→	Critical

■ Non-idealities are more critical for high selectivity membranes operating at high recovery

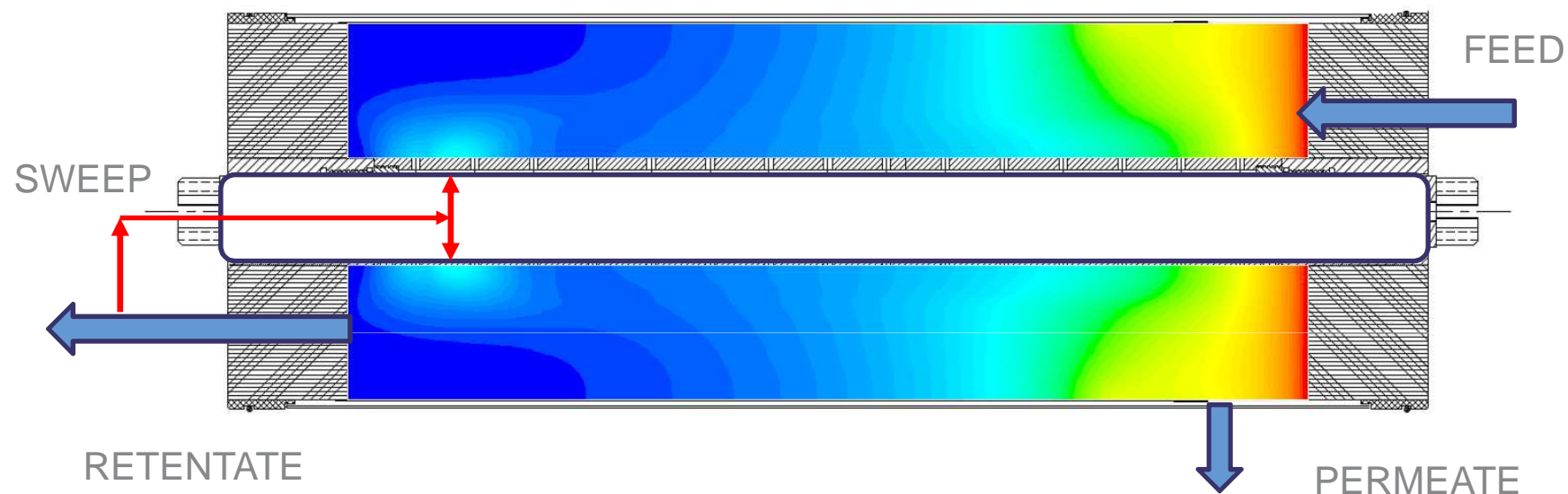
■ Critical elements are different for air separation & CO₂ separation

CFD Model

The driving force for CO₂ permeation is the partial pressure difference between feed and permeate. This force drops as the CO₂ is depleted



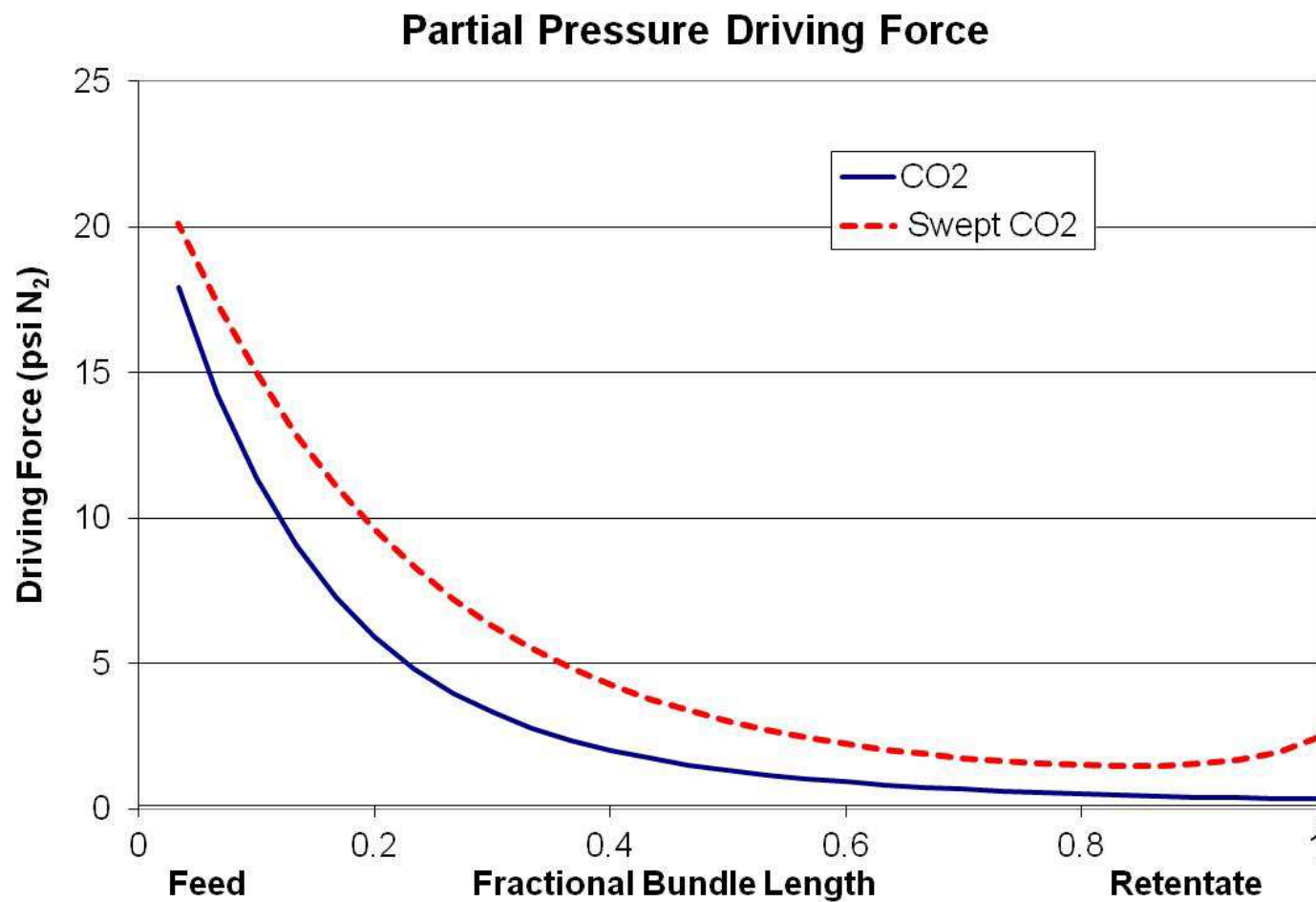
CO₂ partial pressure difference is critical



Addition of Sweep increases driving force across membrane for efficient flue gas separation



Effect of Sweep



The sweep prevents “pinching” of CO₂ at the retentate end while depressing N₂ flux



Thank you

